EEMS0016

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Energy Efficient Connected and Automated Vehicles

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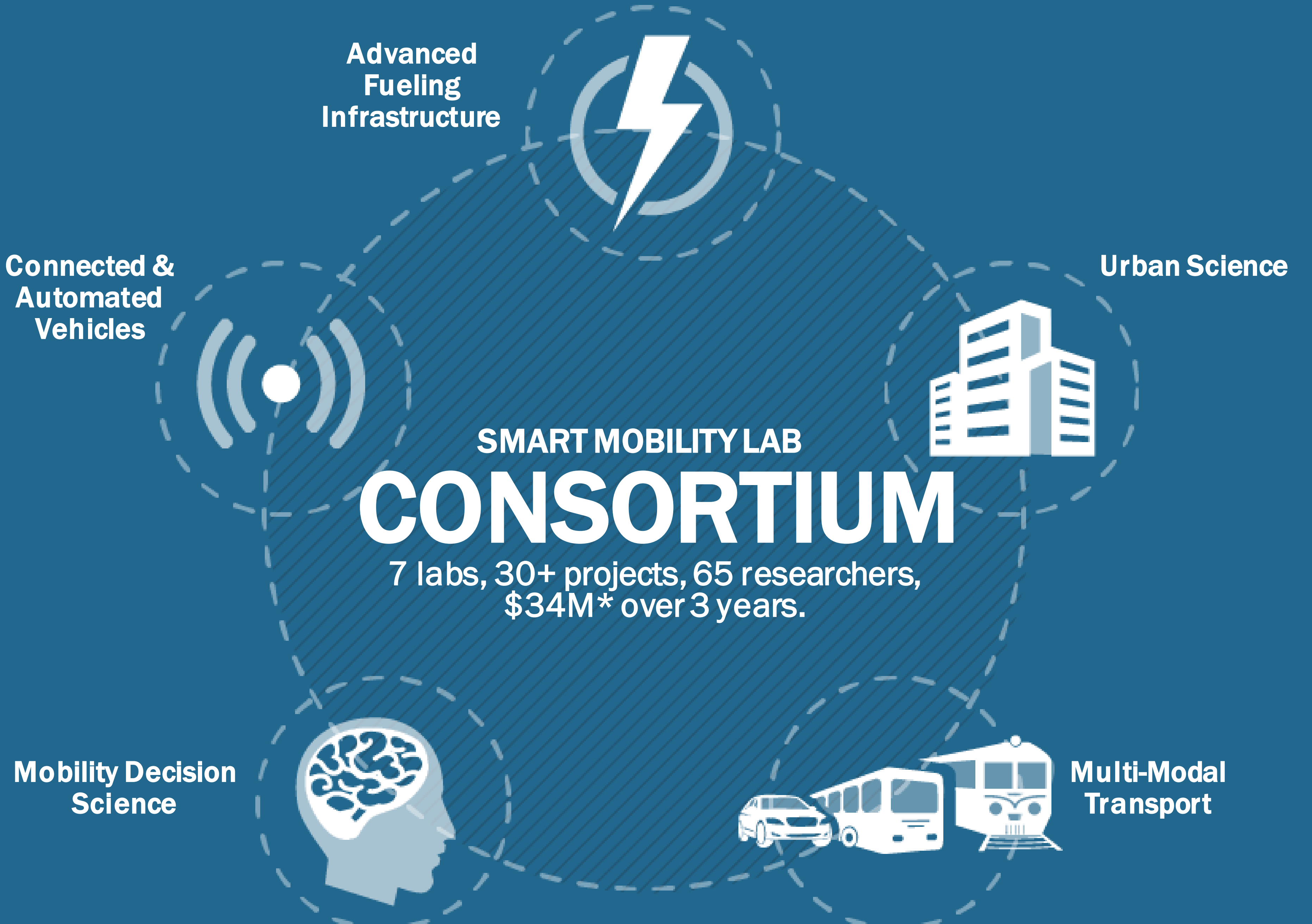
2018 DOE Vehicle Technologies Annual Merit Review - June 19, 2018

ENERGY EFFICIENT MOBILITY SYSTEMS PROGRAM INVESTIGATES

MOBILITY ENERGY PRODUCTIVITY

THROUGH FIVE EEMS ACTIVITY AREAS

- Advanced R&D Projects
- Living Labs
- Smart Mobility Lab Consortium
- HPC4Mobility & Big Transportation Data Analytics
- Core Evaluation & Simulation Tools



*Based on anticipated funding

Project Overview

Timeline

- Project start date : Oct. 2016
- Project end date : Sep. 2019
- Percent complete : 40%

Budget

- FY17 Funding: $836,000
- FY18 Funding Received : $660,000

Partners

- Argonne: lead
- LLNL, LBNL: provide testing data
- TARDEC / Auburn: application

Barriers

- Eco-driving research rarely integrates **advanced powertrain technologies**
- Combining dynamics and powertrain control results in **complex control problems**
- **Real-world implementation** often challenging
- Many **exogenous factors** (e.g. traffic), affect energy saving potential of eco-driving
- **Lack of practical tools** for “powertrain-aware” eco-driving algorithm development

Project Objective and Relevance to VTO EEMS

Eco-Driving

Energy-efficiency through connectivity and automated driving

Optimal control theory applied to CAVs, with powertrain and longitudinal speed as degrees of freedom

Online controller implementation using model-predictive framework

Application to multiple powertrain (e.g. HEV, EV) and scenarios (cruise-control, car-following, etc.)

VTO EEMS STRATEGIC GOAL #2
Identify & support **early stage R&D** to develop innovative technologies that **enable energy efficient** future mobility systems.

CAV Simulation

RoadRunner: a framework for simulation of connectivity, automation and advanced vehicle powertrain technologies

Autonomie high-fidelity powertrain models …
+ multiple vehicles
+ road model (speed limits, traffic lights, etc.)
+ driver (human or automated) reacting his environment
+ information flows (V2V, V2I, sensors, etc.)

VTO EEMS STRATEGIC GOAL #1
Develop **new tools**, techniques, & core capabilities to understand & identify the most important levers to improve the energy productivity of future integrated mobility systems.

Approach: Eco-Driving Research

Information

Current and Look-Ahead

Speed and powertrain control for energy efficiency

Control variables*: engine/motor torque, gear, brake force*

States*: speed, SOC, position, etc.*

Constraints*: safety (speed limit, other vehicles), powertrain (limits for battery, engine, etc.), travel time and drivability*

Optimization

Finding analytical or numerical solution to control problem

- Optimal control theory
- Offline, open-loop
- Outputs trajectories (e.g. torque, gear, etc.)

☑ Long-range cruise control Conv., HEV and EV

☑ Periodic "pulse-and-glide" for Conv.

☐ Car-following and fixed obstacle approach

Predictive Control

Online implementation with feedback loop

- Executes optimal trajectory with periodical updates
- In Simulink/RoadRunner
- Mimics I/Os and dynamic loops of online controllers

☑ MPC with Quadratic Programming in RoadRunner for torque control

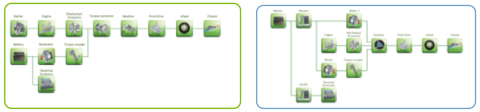
☐ Dynamic programming and optimal control theory as optimization methods

Approach: RoadRunner, a Multi-Vehicle, Powertrain and Road Environment Simulation Framework

1. Define Scenario and Select Powertrain

Example:
Route: 3.4 mi / 14 TL / 2 stops / Limit =25, 30, 45 mph
Can be extracted automatically from HERE maps

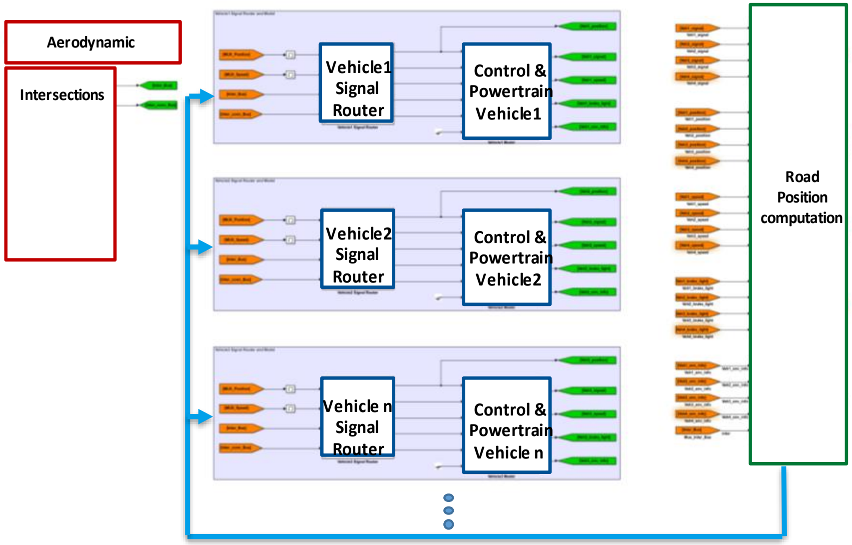
Vehicles: Conventional or Micro-HEV or …



Automated Model Building

Scenario: Human vs. CAV w/ **eco-approach** and CACC

2. Scenario Simulation

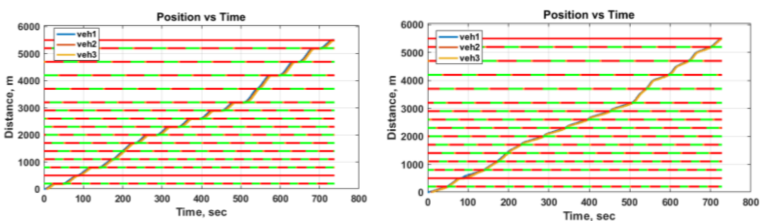


- *Powertrain (each veh.)*
- *Human driver, or automated driving controller (each veh.)*
- *Intersection (w/ traffic lights)*
- *Route specs (grade, speed limits, etc.)*
- *Information links between these components.*
- *e.g. Visual, Sensors, V2V, V2I*

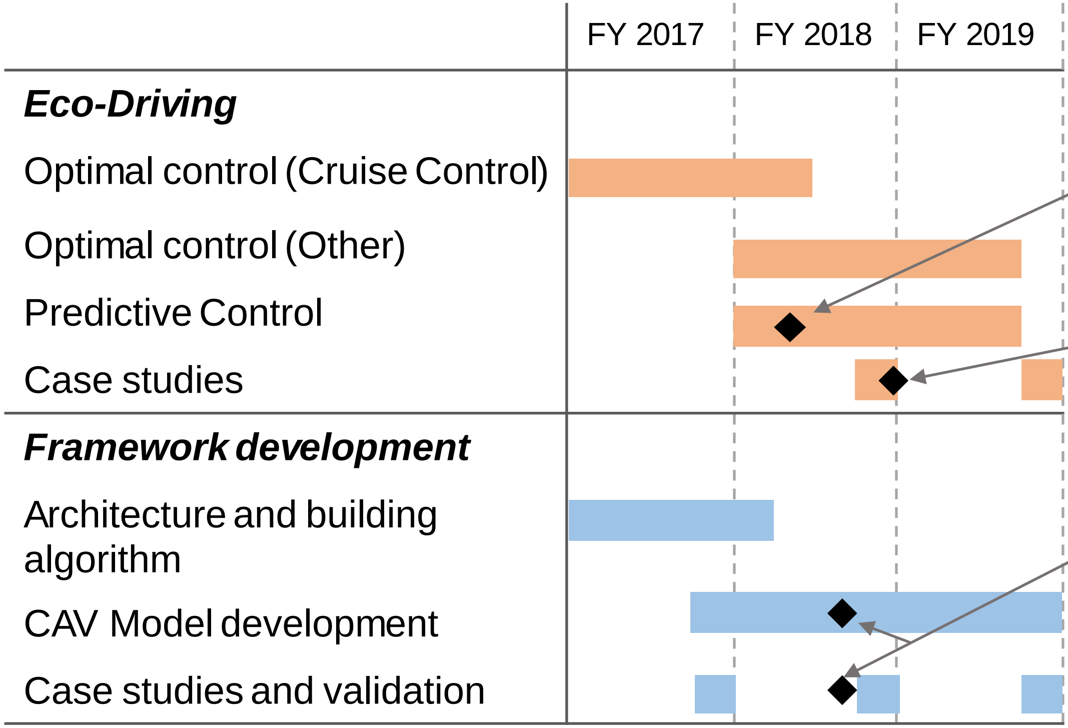
3. Analyze Simulation Results

Example scenario: **Eco-approach**

Human/Baseline **CAVs**



Milestones



2018Q2	✓*Complete*
Close-loop eco-driving controller	

2018Q4	*On Track*
Energy impact of eco-driving strategies under different scenarios	

2018Q3	*On Track*
Validated model of a CAV	

2018 Go/No-go: availability of test data for validation

2017	✓*Complete*
RoadRunner: First prototype Eco-driving: Optimal cruise control for HEV	

2019	**On Track**
RoadRunner: improved models & validation Eco-driving: online close-loop implementation of CAV eco-driving for multiple powertrain and scenarios	

TECHNICAL ACCOMPLISHMENTS

RoadRunner Improvements to Support Studies and Accelerate Public Release

- **Architecture and Automated Building**
  - Improved integration with Autonomie building algorithms
  - Vehicle powertrain models no longer need to be compiled into S-functions
  - More flexible architecture allows the simulation of more scenarios

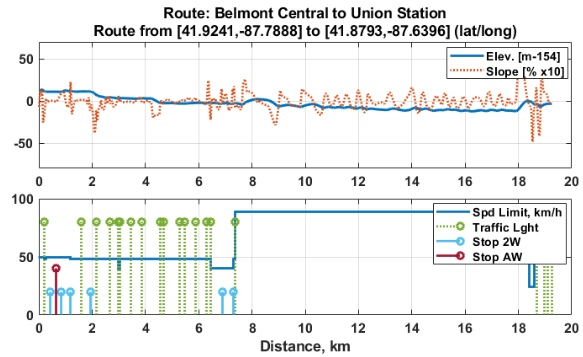
    Example: moved energy management inside automated driving to enable coordinated control of speed and powertrain
  - Integration with HERE maps API to extract route attributes (position of traffic lights, grade, speed limits, etc.)
- **CAV Models and Scenarios**
  - Merged car-following and free-flow driving scenarios
  - Updated the baseline 'human' driver models for car-following to maintain a safe distance with preceding vehicle.
  - Integrated aero drag reduction coefficients for short-gap driving (wind tunnel data* from LLNL)
  - Working with LBNL test data to validate truck-platooning model
- **Interface**
  - Improved the script files for easier build and launch of scenarios
  - All process files can be added as library of Autonomie R16 and working on the integration of RoadRunner into AMBER in preparation for 1st release (EEMS013 Core Modeling)

*Salari, K. and Ortega, J., "Experimental Investigation of Aerodynamic benefits of Class 8 Tractor-Trailer Platooning," SAE Technical Paper 2018-01-0732

Implemented an Eco-Approach Algorithm in RoadRunner for a String of Vehicles

Route Data from HERE Maps

12 miles
speed limits: 30, 25, and 55 mph,
20 traffic lights, 7 stop signs.

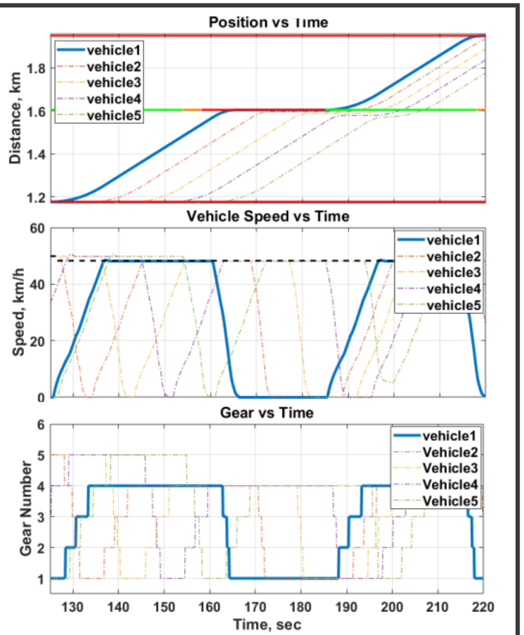


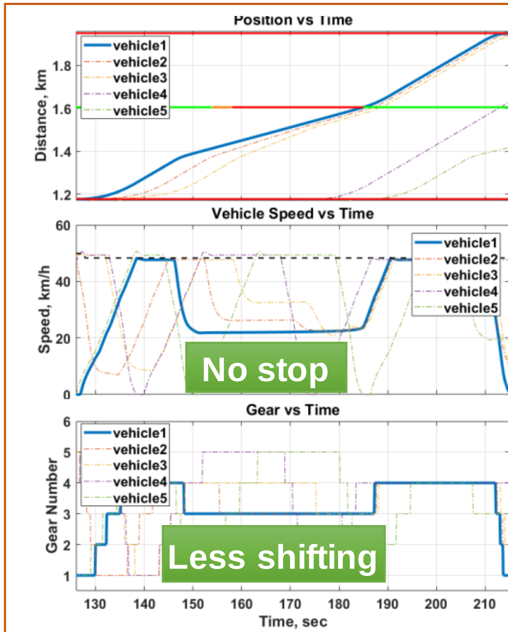
conventional internal combustion engine based vehicle

Vehicle Spec. (Conv.)	values
Vehicle mass (kg)	1,587
Drag coefficient	0.311
Engine	135kW (2.2L gasoline)
Transmission	6 speed automatic

Human/Baseline Driver

- Driver only knows current signal state;
- Lead veh. cruises at speed limit, brakes/accelerates according to a pre-defined profile
- Following vehicles keep safe distance to lead





Connected Eco-Driving

- Vehicle knows current and future state of signal 250m ahead
- Eco-driving algorithm reduces speed to avoid stops
- Following vehicles also know signal state

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Kim, N., Karbowski, D., and Rousseau, A.,
A Modeling Framework for Connectivity and Automation Co-simulation
SAE Technical Paper 2018-01-0607, 2018

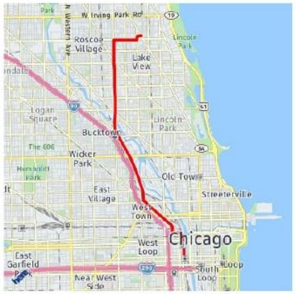
Energy Savings and Powertrain Operations

Energy Savings Highly Dependent on Scenario

Also depends on type and number of vehicles, traffic light sequence and phase, signal info range, etc.

Route #1 = 4.8% Savings

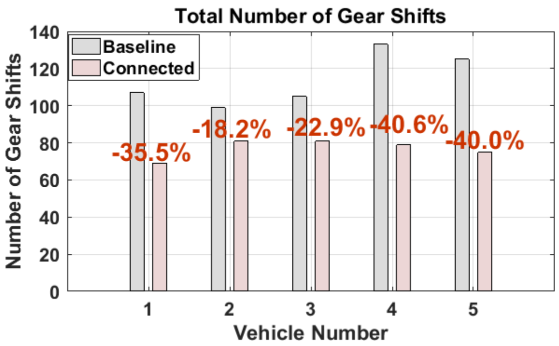
Route #2 = 9.2% Savings



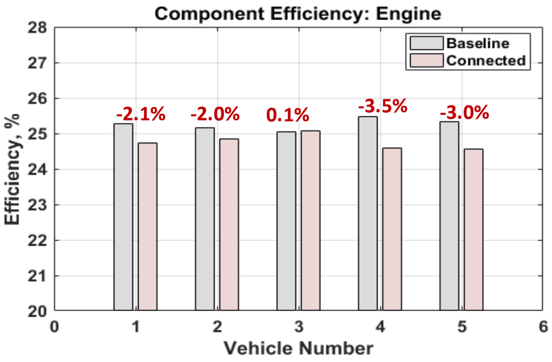
Positive and Negative Impact on Powertrain Operations

Eco-approach algorithm used in study NOT "powertrain-aware"

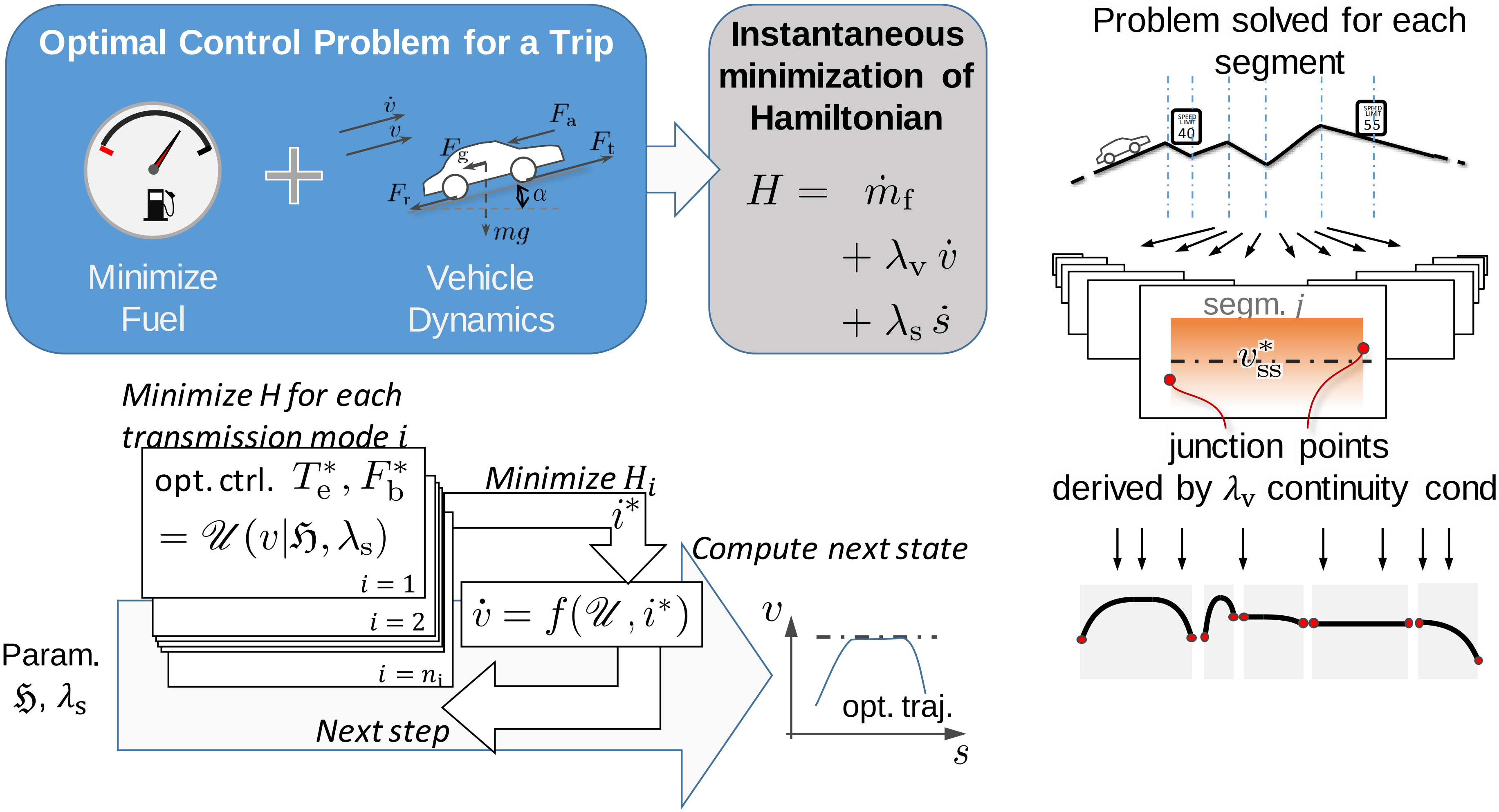
Less Shifting Events



Lower Engine Efficiency

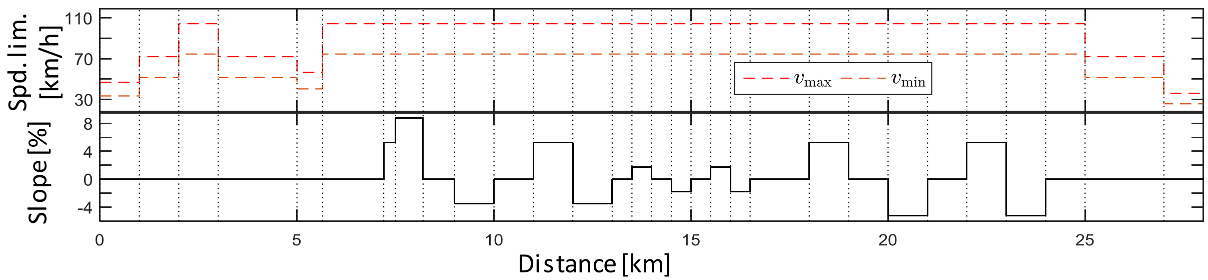


Eco-Driving: Optimal Control Theory Applied to Cruise-Control Algorithm

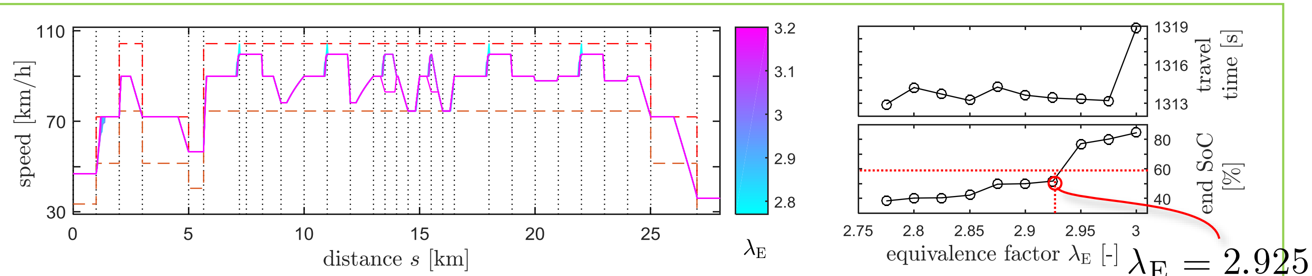


Case Study for Parallel HEV: 6% savings

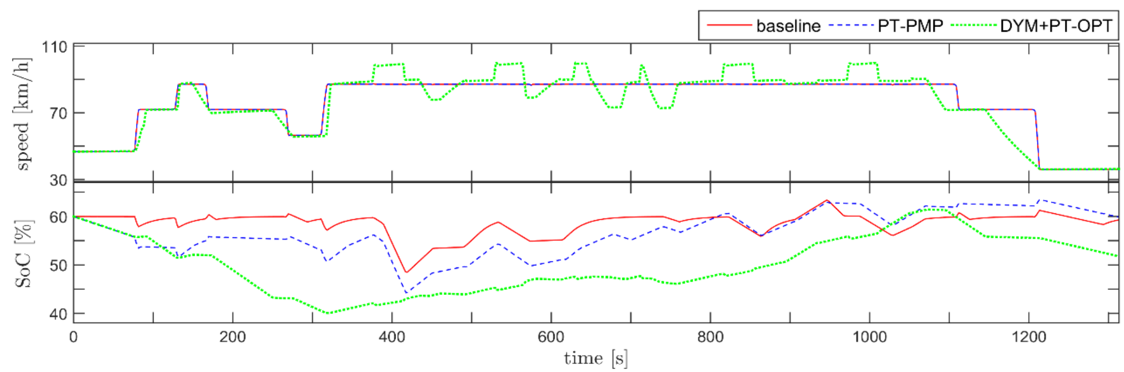
Artificial route with piecew. const. slope



Optimization of speed profile while adapting eq. factor λ_{E}



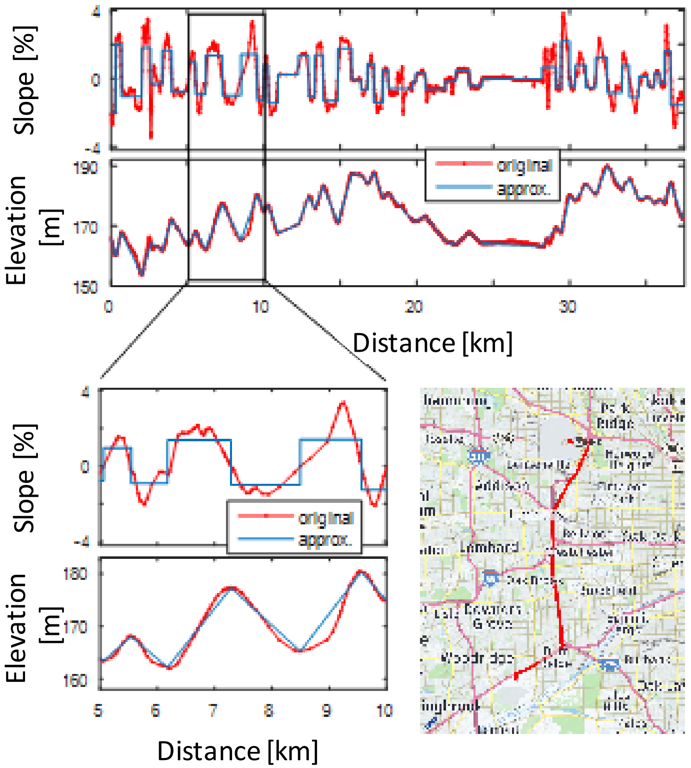
Fuel saving (w/ same travel time):
6% vs. rule-based ctrl.
3.3% vs. powertrain ctrl. opt. alone



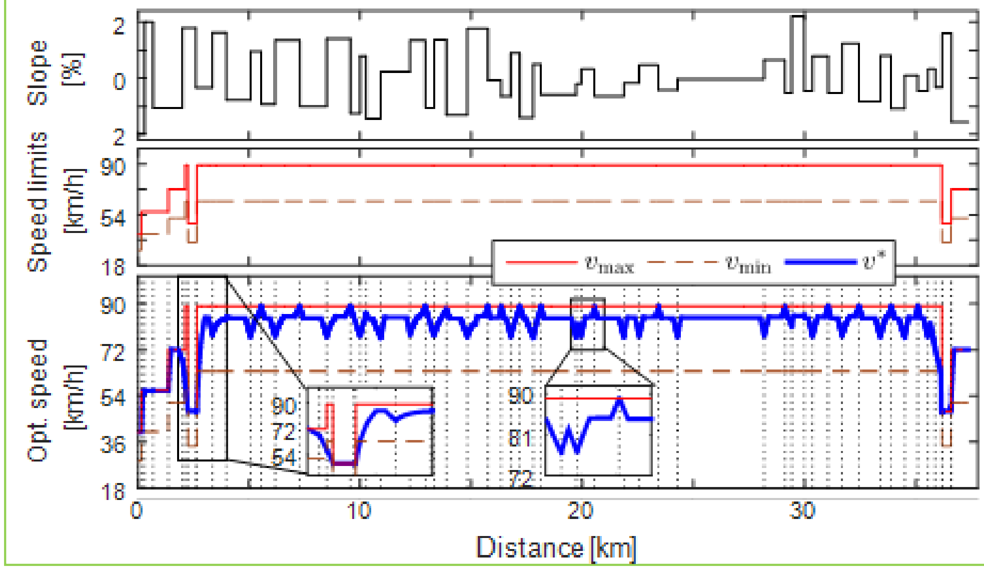
Daliang Shen, D. Karbowski, Jongryeol Jeong, Namdoo Kim, and Aymeric Rousseau
Energy-Efficient Cruise Control Using Optimal Control for a Hybrid Electric Vehicle
EVS30, Oct 2017

Case Study for Conventional: 8% savings

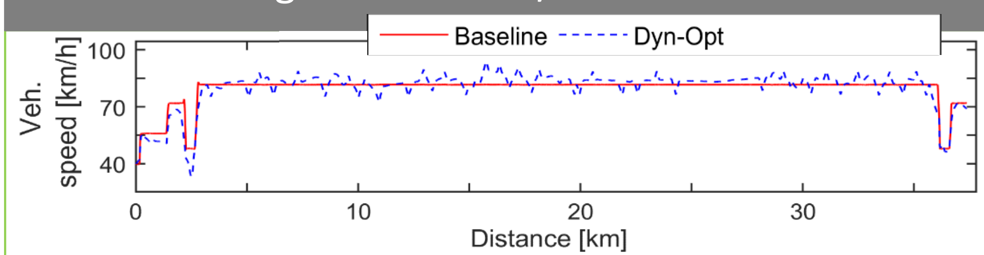
Simplification of real world slope into piecewise constant



Optimization result

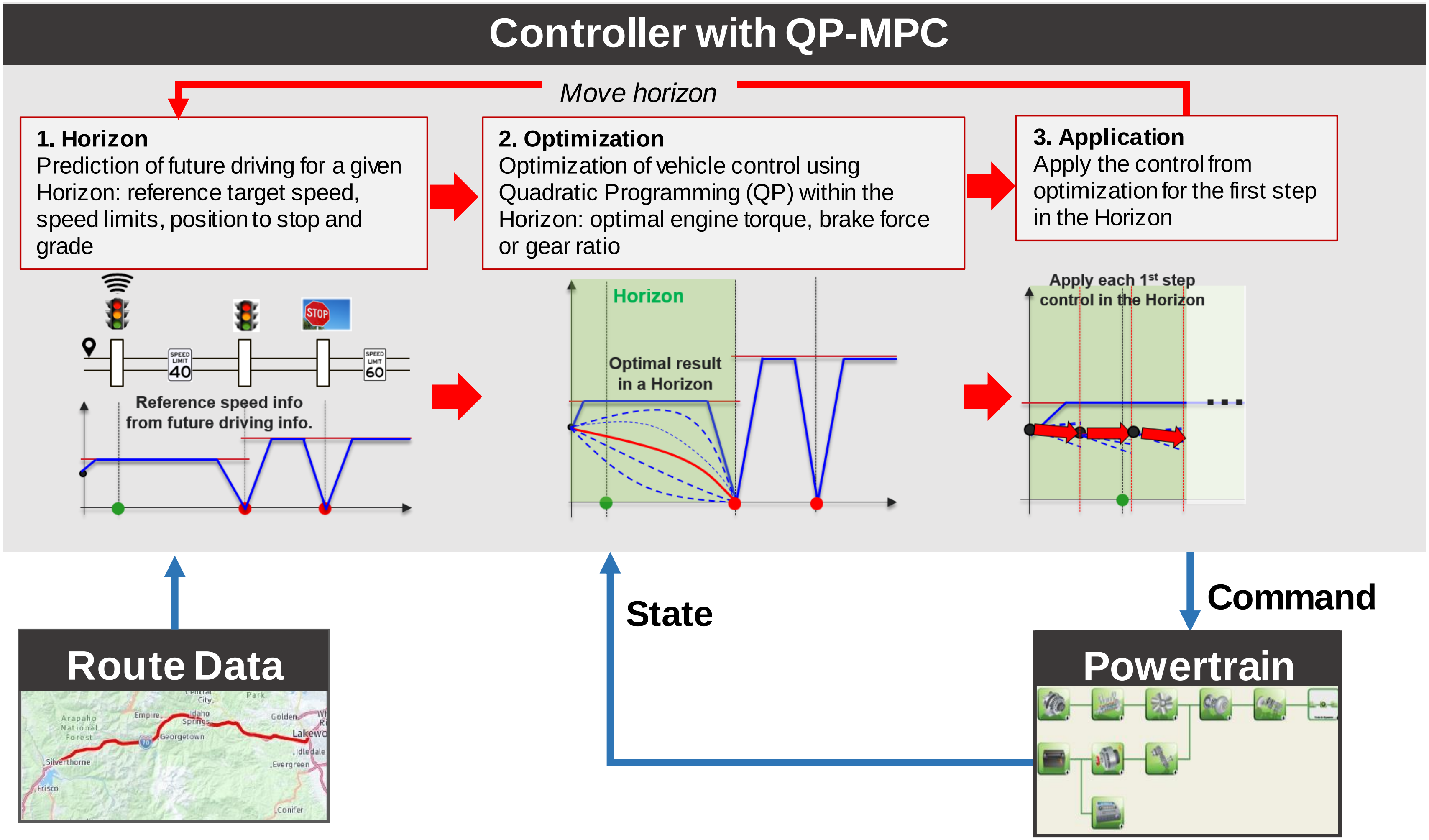


8% fuel saving vs. human w/ same travel time



Shen, D., Karbowski, D., and Rousseau, A.,
Fuel Efficient Speed Optimization for Real-World Highway Cruising,
SAE Technical Paper 2018-01-0589, 2018

Model-Predictive Control Implemented in RoadRunner; Critical Step for Future Work

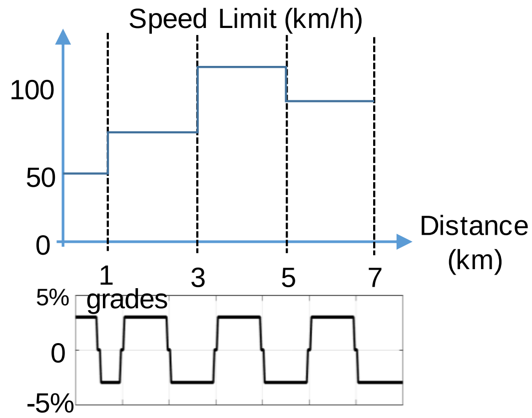


Online MPC Controller Shows 3% to 7% Fuel Savings in Cruise-Control Case Study

Setup

- Conventional midsize w/ 6 speed trans.
- Baseline = follow speed limits
- MPC Cruise-Control only active above 70 km/h
- Horizon = 500m
- MPC only controls torque; shifting logic is rule-based

Test Cycles



Routes

Route 1: Argonne to Chicago

Route 2: I-70 Denver to Silverthorne

Results

4% to 7 % Fuel savings

+ slower travel

3% to 4.5% Fuel savings

Response to Previous Year Reviewers' Comments

*"The levers that the optimization will be turning in Autonomie […] may be outside of the **drivability constraints** or actuation abilities of real-world powertrains".*

Moving to an online implementation of the eco-driving algorithms in a framework with models that include **dynamics** (e.g. shifting events) allows to pay closer attention to **drivability constraints**.

*"There was no mention of methods of **prediction** and **uncertainty in prediction** discussed in the presentation"*

The focus of this project is to develop methods that use knowledge (from sensors, V2X, etc.) about the driving environment to operate the vehicle more efficiently. Prediction and prediction uncertainty will be considered at **later** stages. However, thanks to the online implementation, there is a **close-loop feedback** to the eco-driving algorithm, i.e. the optimal command is re-evaluated periodically, thus reacting to short-term changes in the environment.

*"The reviewer was unsure how the results would be taken to **practice** and who the **target audience** was for the work"*

The target audience are research organizations, **advanced R&D** at OEMs, suppliers and eco-driving technology startups seeking to use connectivity and automation for energy-efficiency. We use Model-Based Systems Engineering (MBSE), as practiced in the industry. RoadRunner will eventually be **released to the public** (early FY19), and the online, close-loop implementation of optimal control **replicates the I/Os and the information flows to actual ECUs**. However, we do not consider integration with other layers of control, esp. ones in charge of safe movements

Partnerships and Collaborations

Lawrence Livermore National Laboratory	LLNL provided aerodynamic drag reduction coefficients from 3D modeling and wind tunnel
BERKELEY LAB	LBNL tests platooning trucks and provides results and data from real-world testing
NREL NATIONAL RENEWABLE ENERGY LABORATORY	NREL shared reports and insights from truck platooning testing
AUBURN UNIVERSITY TARDEC	Platooning truck data RoadRunner used for control development
here	Digital maps with detailed road features

Remaining Challenges and Barriers

- **Data for validation of baseline RoadRunner models:**
  - Data that would have all the necessary signals and scope are rare
  - Data silos make access difficult
- **In-vehicle validation of eco-driving algorithms**
  - Would require access to powertrain supervisory ECU
  - Would necessitate integration with other control layers (e.g. safety)
  - Some scenarios require more than one vehicle or V2I communication
- **Modeling human driving**: human behavior is not fully deterministic, and depends on individuals (e.g. aggressive vs passive drivers)
- **Representativeness of the results**: need to simulate the right mix and number of scenarios to get representative energy saving figures.

Proposed Future Research

- **RoadRunner**
  - Improve human driver model, and validate with real-world driving data
  - Develop a library of CAV scenarios, and perform validation
- **Eco-Driving**
  - Optimal control theory: Complete application of optimal control theory to CAV scenarios
  - Predictive control: implement non-linear/quadratic optimization techniques to allow command of all control variables
  - Develop "all-scenarios" controller
- **Case studies**
  - Quantify the energy impact uncertainties of different technologies (e.g. eco-approach) using large case studies
  - Quantify the impact of component technology benefits and operating conditions to guide VTO R&D portfolio
  - Improve our understanding of fuel savings levers
  - Identify optimum control calibrations

Summary

In FY17/18, we have laid the **foundations**, generated **results**

- ✓ **Developed RoadRunner**, a tool enabling the development and evaluation of eco-driving techniques
- ✓ **Solved optimal "eco-driving" control problem** for multiple powertrains (cruise-control) (6 to 8% savings)
- ✓ **Developed first implementation** of a closed-loop eco-driving controller with predictive control (3 to 7% savings)

Next, on track for successful conclusion

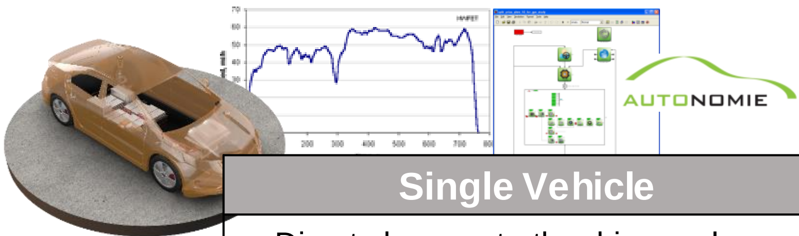
- Will complete development of CAV scenarios and controllers
- Will run large-scale case studies to better assess energy saving potential of CAVs and Eco-Driving

Fostering the development of **energy-efficient CAVs**

- Advancing **eco-driving control science**, theory and implementation
- Shedding light on the intersection of **advanced powertrain technologies** and CAVs
- Providing **tools and methods** needed for eco-driving work to the research community and industry

TECHNICAL BACK-UP SLIDES

RoadRunner Filling a Need among Existing Tools



Single Vehicle

- Direct changes to the drive cycles can model CAVs
- Modeling of interactions, control of speed, etc. impossible

Traffic-flow Microsimulation

- Can model interactions between vehicles and infrastructure (to some extent)
- Focus on detailed traffic flow, control
- Can include powertrain models/control only in compiled form

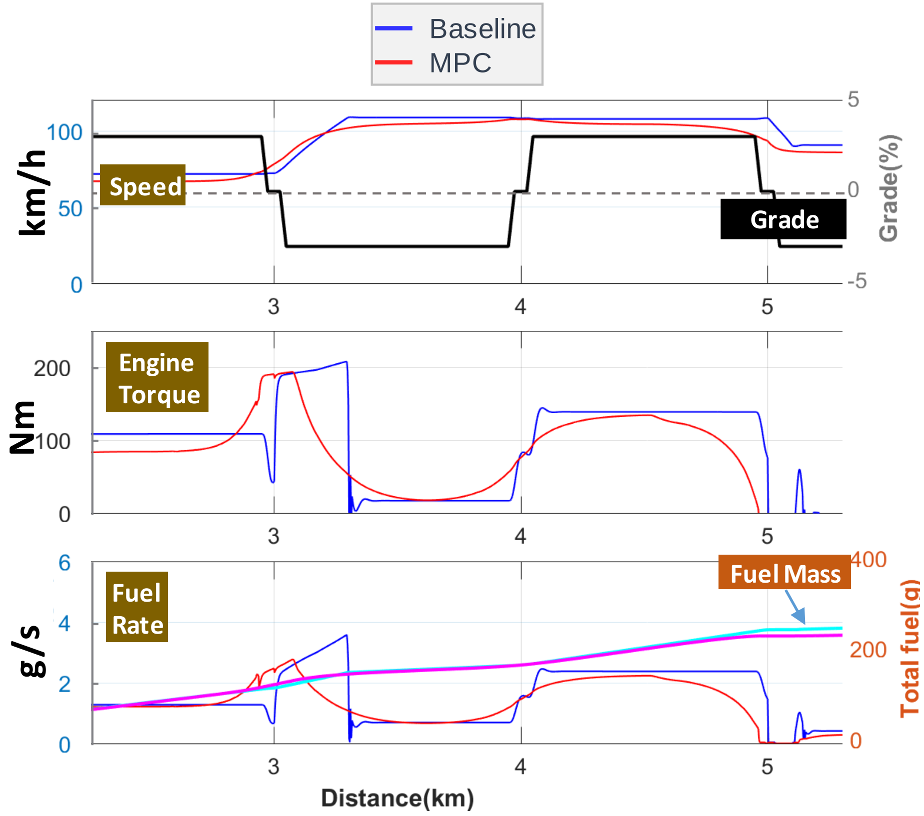
Powertrain/Energy Accuracy

Traffic Accuracy

RoadRunner

- Simulate both powertrain and driving environment (drivers, vehicles, infrastructure)
- Easily run a broad range of route scenarios
- Integrate with Autonomie powertrain models
- Provide an environment for development and evaluation of eco-driving algorithms for CAVs

Example of Operations with MPC



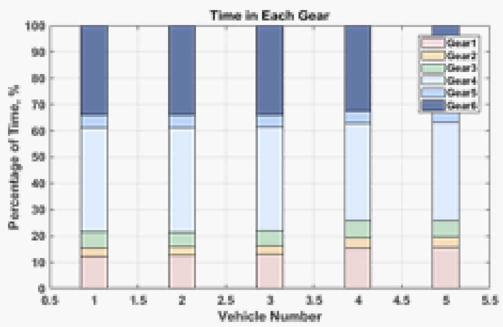
Connected/Automated Vehicles Will Be Driven Differently, which Will Affect Transmission/Engine Use and Design

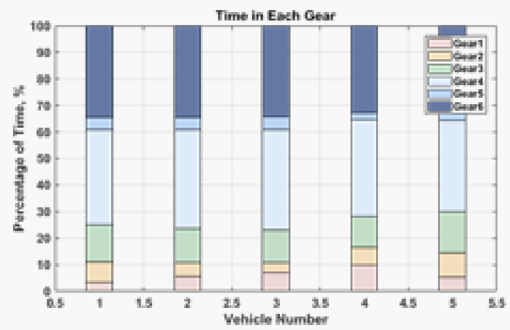
Human/Baseline Driver

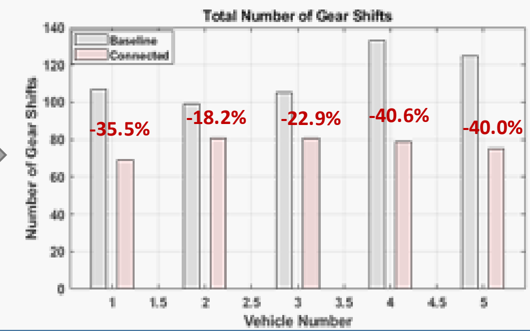
Connected Eco-Driving

Eco-Approach Example (Transmission): 32.3% Reduction in the Number of Shifts

- The use of a larger gear ratio for transmission is reduced, and the number of shifts can be drastically reduced.

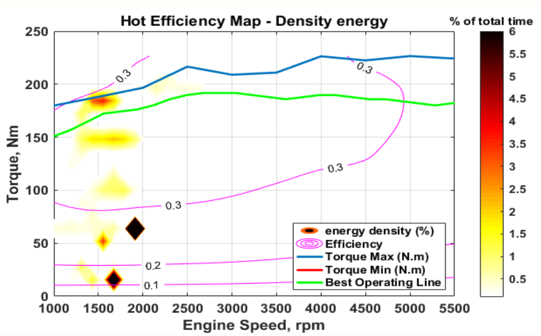


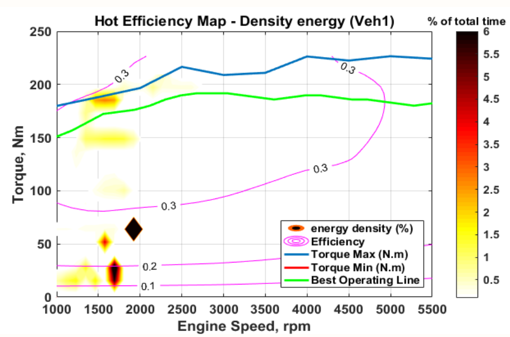


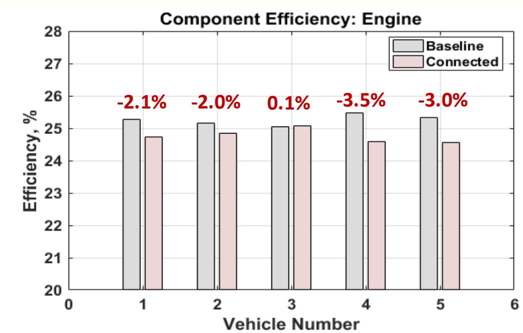


Eco-Approach Example (Engine): Operating in Lower Torque Range

- The reduction of demand for acceleration leads to further operation in the low torque region of the engine. (i.e. slightly decrease of engine average efficiency)







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